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US 3873825 A

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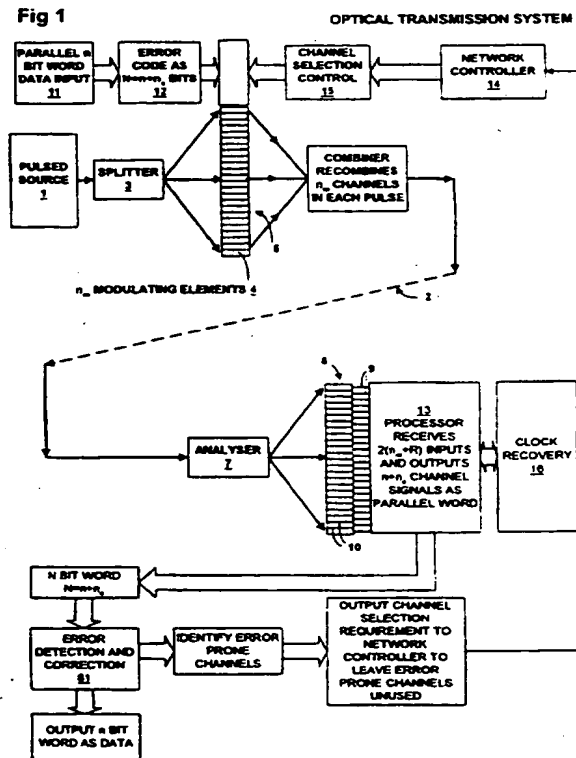
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14/08  
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(54) Abstract Title

**Multiplexed transmission of optical signals**

(57) Optical signals in an optical communication system are transmitted as a train of optical pulses which are multiplexed to provide a large number of channels. Error correction coding is applied to data carried by the channels using both interchannel coding and serial coding of individual channels. When multiplexed by wavelength division multiplexing, a waveguide array (32) is used as a dispersive device having a characteristic of frequency selectivity which is locked by a monitoring and control system to a set of spectral lines ( $f_1$ - $f_7$ ) from the single pulsed laser which generates the pulses. In the receiver, clock signals are generated by extracting clock signals from the earliest and latest received channel signals and performing interpolation to obtain clock signals for the remaining channels. When multiplexed using a spectral modulation technique, individual channels are represented by distinct sinusoidal modulations in frequency space which are then detected in the receiver by Mach-Zehnder filters (73). When using either method of multiplexing, a receiver has a greater number of detectors than the number of channels to be detected to allow detection to accommodate systematic drift in parameter values of the measurable parameter associated with each channel. Error detection coding is used in each channel as a basis for selecting channels to carry a first data stream, the remaining non-selected channels being used to carry a second data stream in which data may be transmitted at a lower rate suitable to the error rate performance of those channels or alternatively data may be replaced by an error detecting code to continue monitoring error rate performance.

Fig 1



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Fig 1

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OPTICAL TRANSMISSION SYSTEM

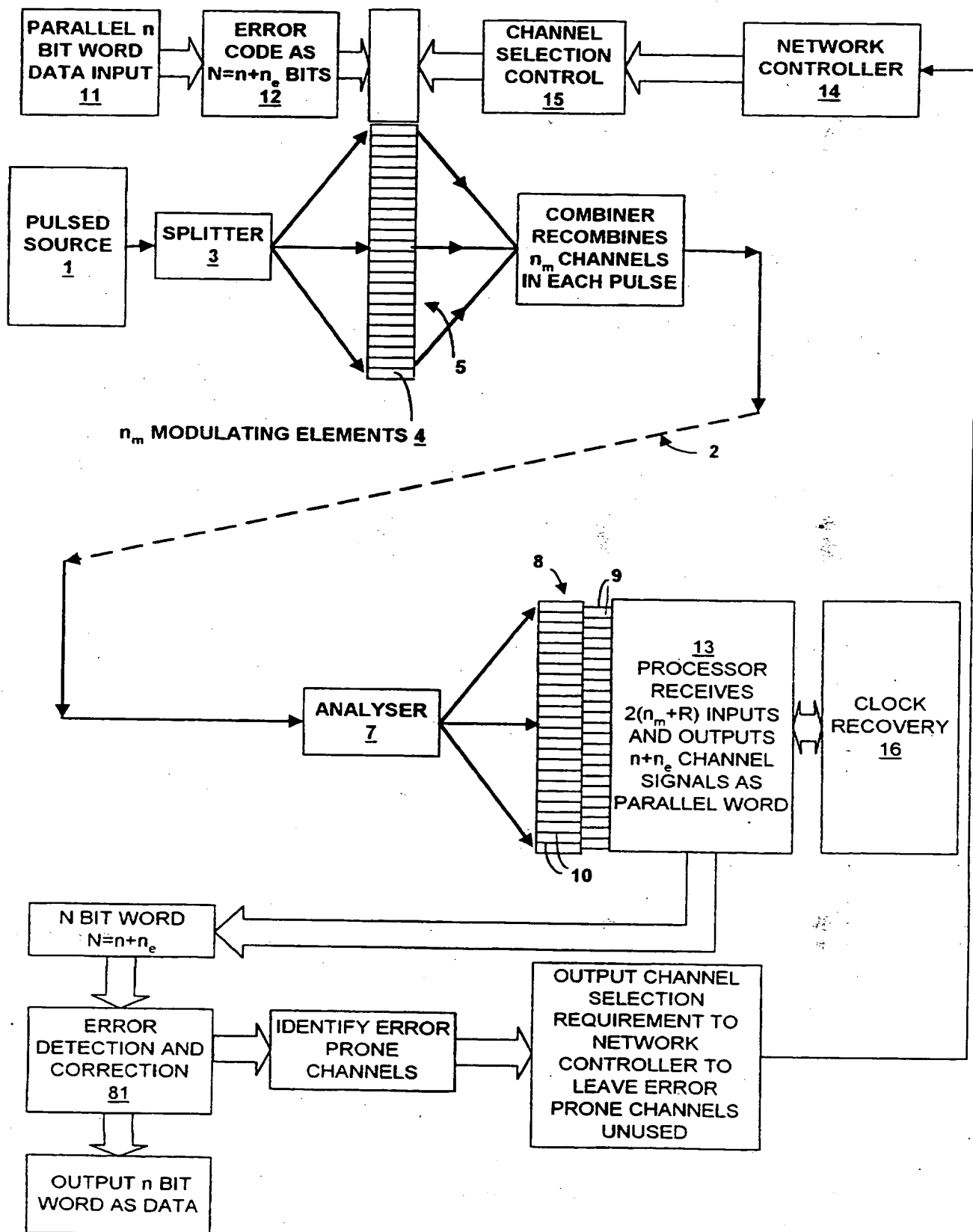
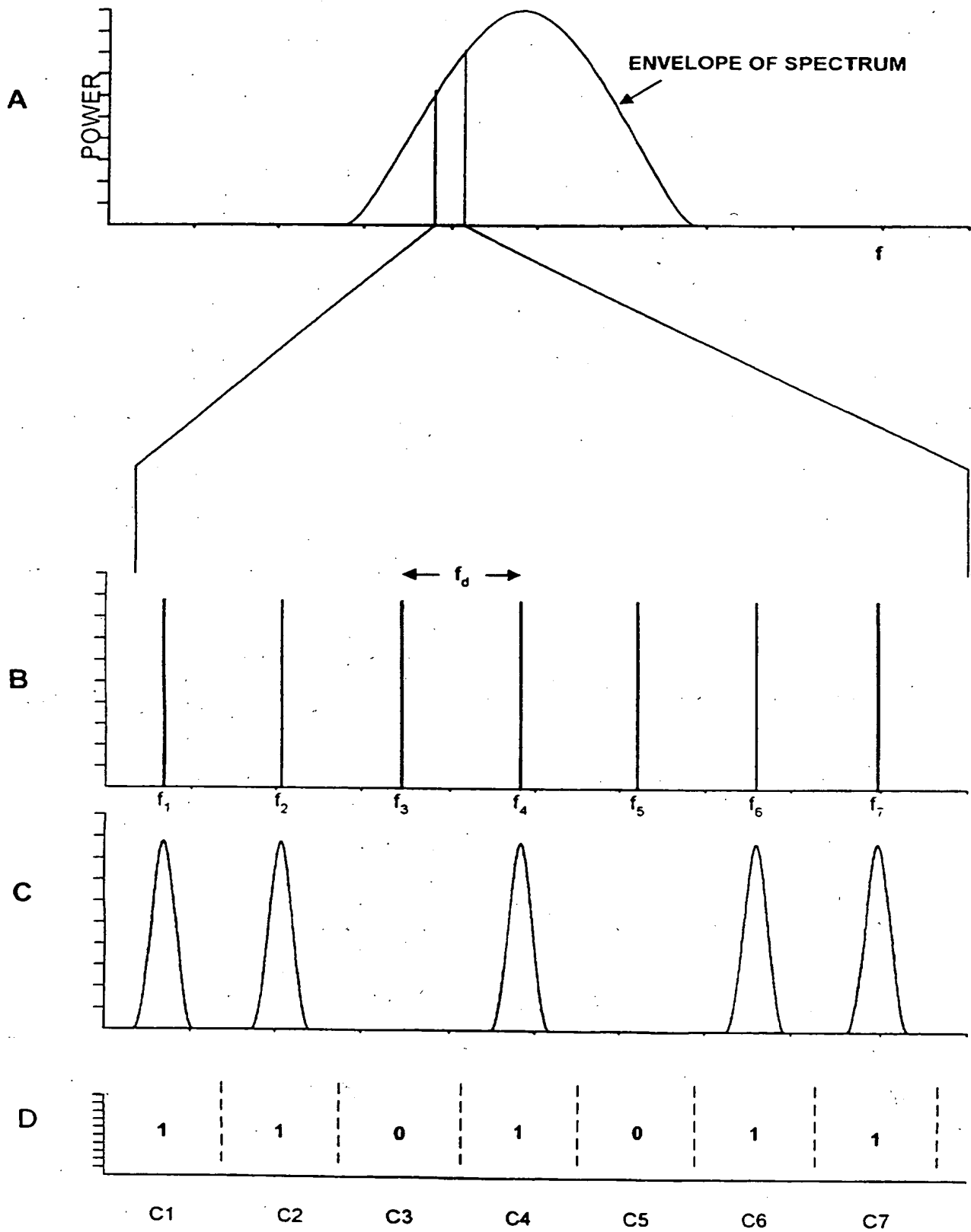


Fig 2

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SPECTRUM OF SOURCE



WAVELENGTH SPLITTER

Fig 3

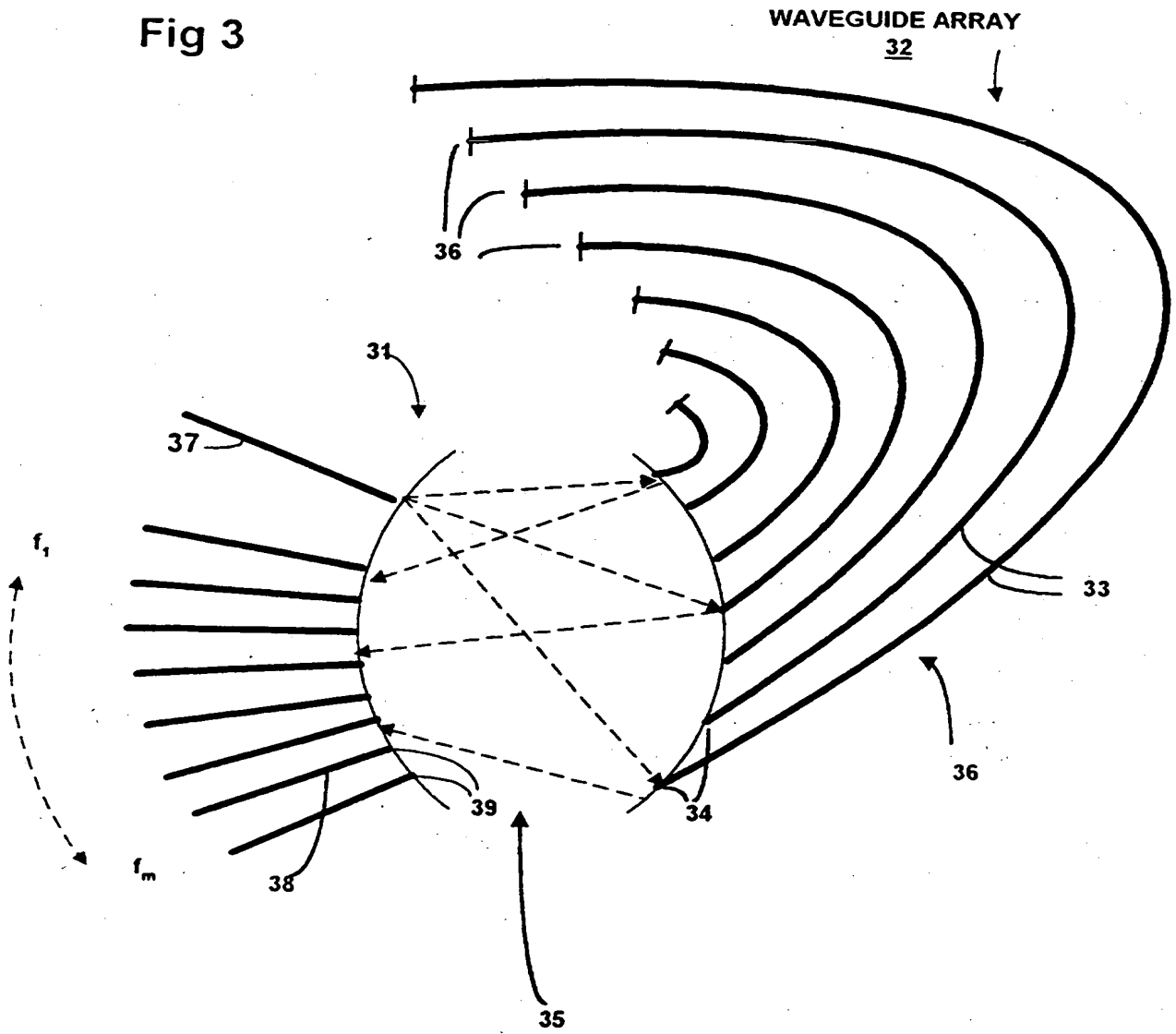


Fig 4

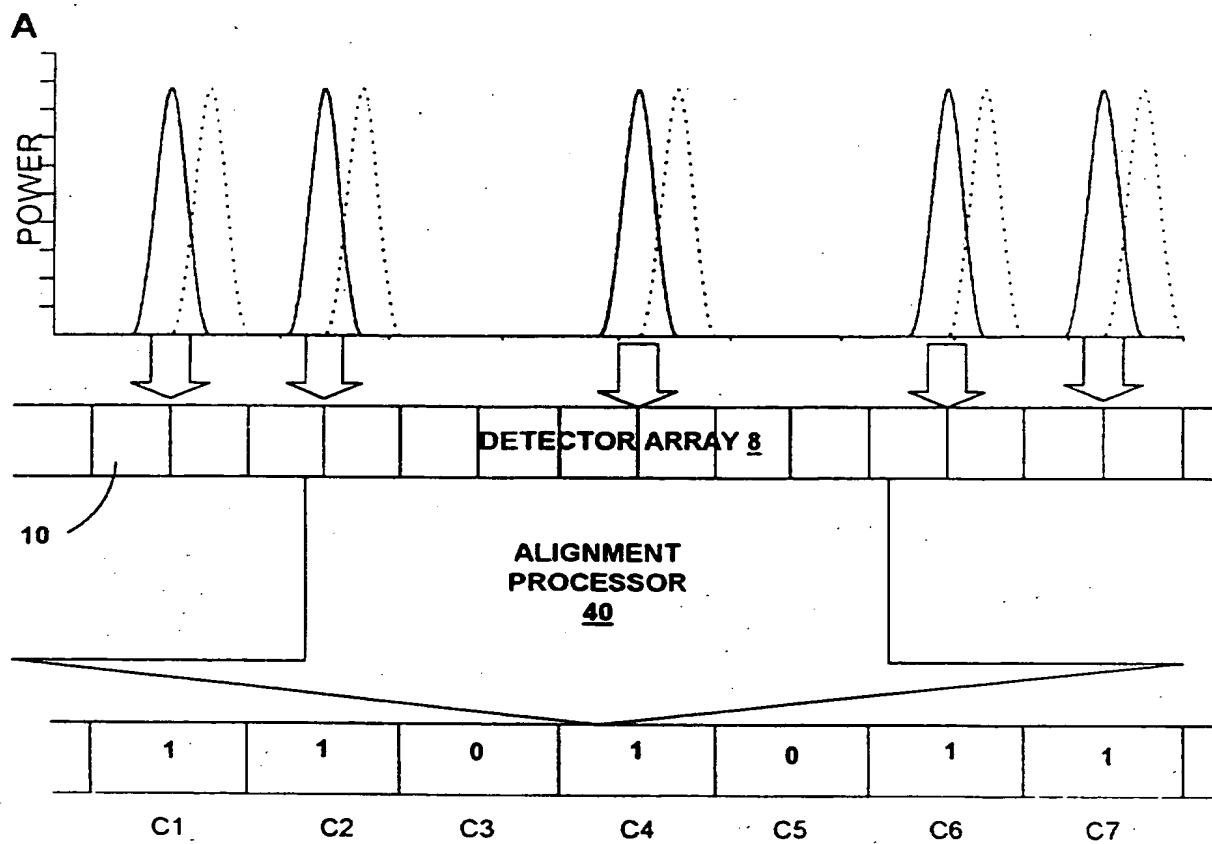
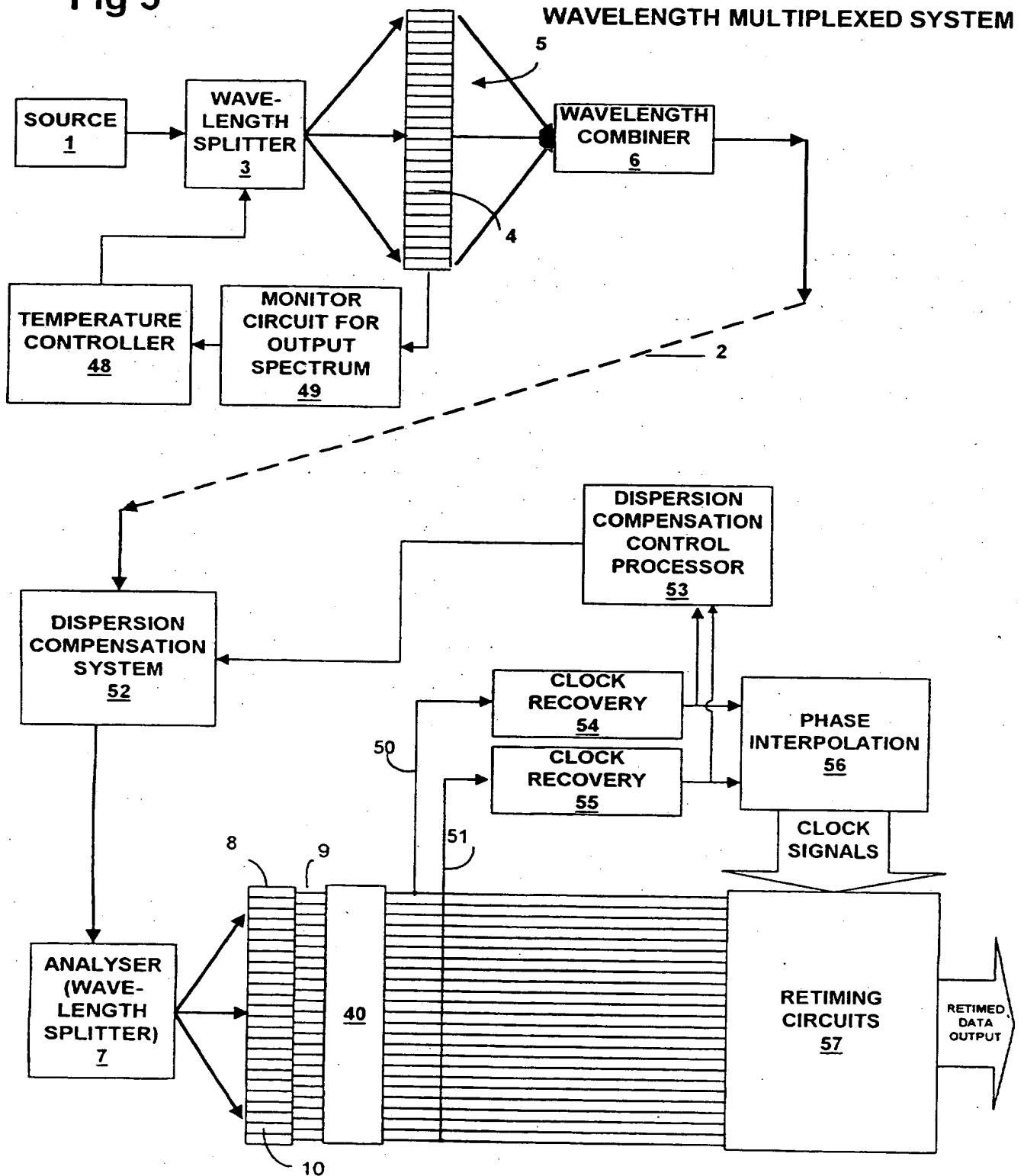
DETECTOR ARRAY FOR WDM WITH DOUBLED  
DETECTOR ELEMENTS

Fig 5



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Fig 6A

FOURIER MODULATOR

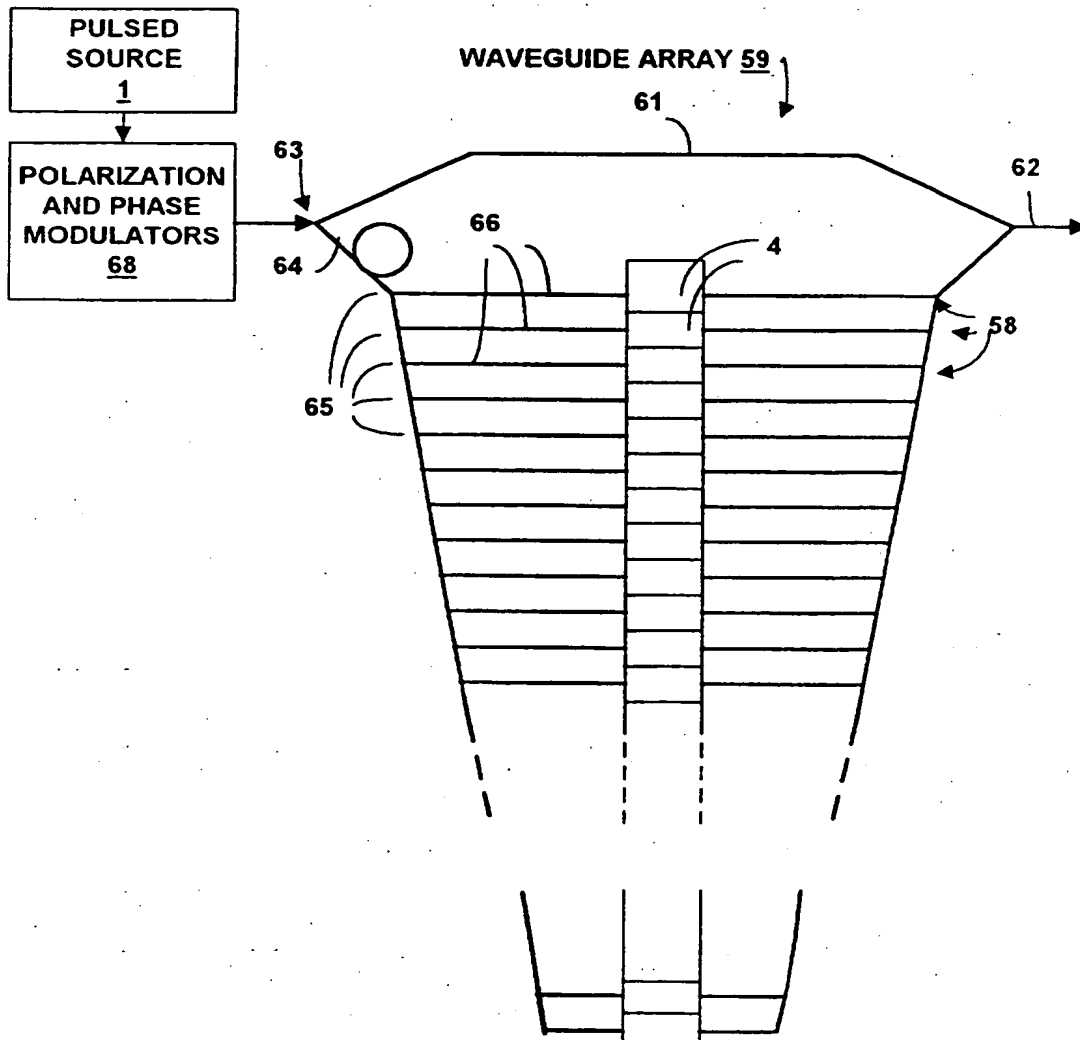
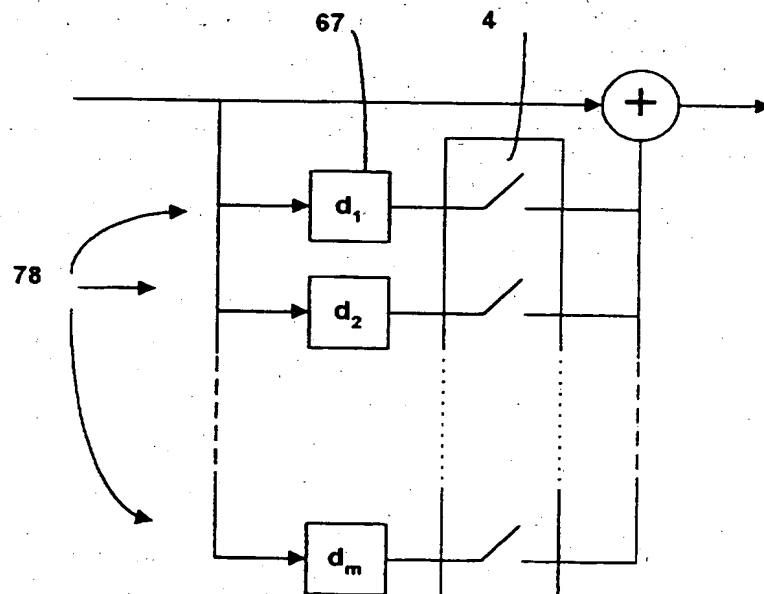


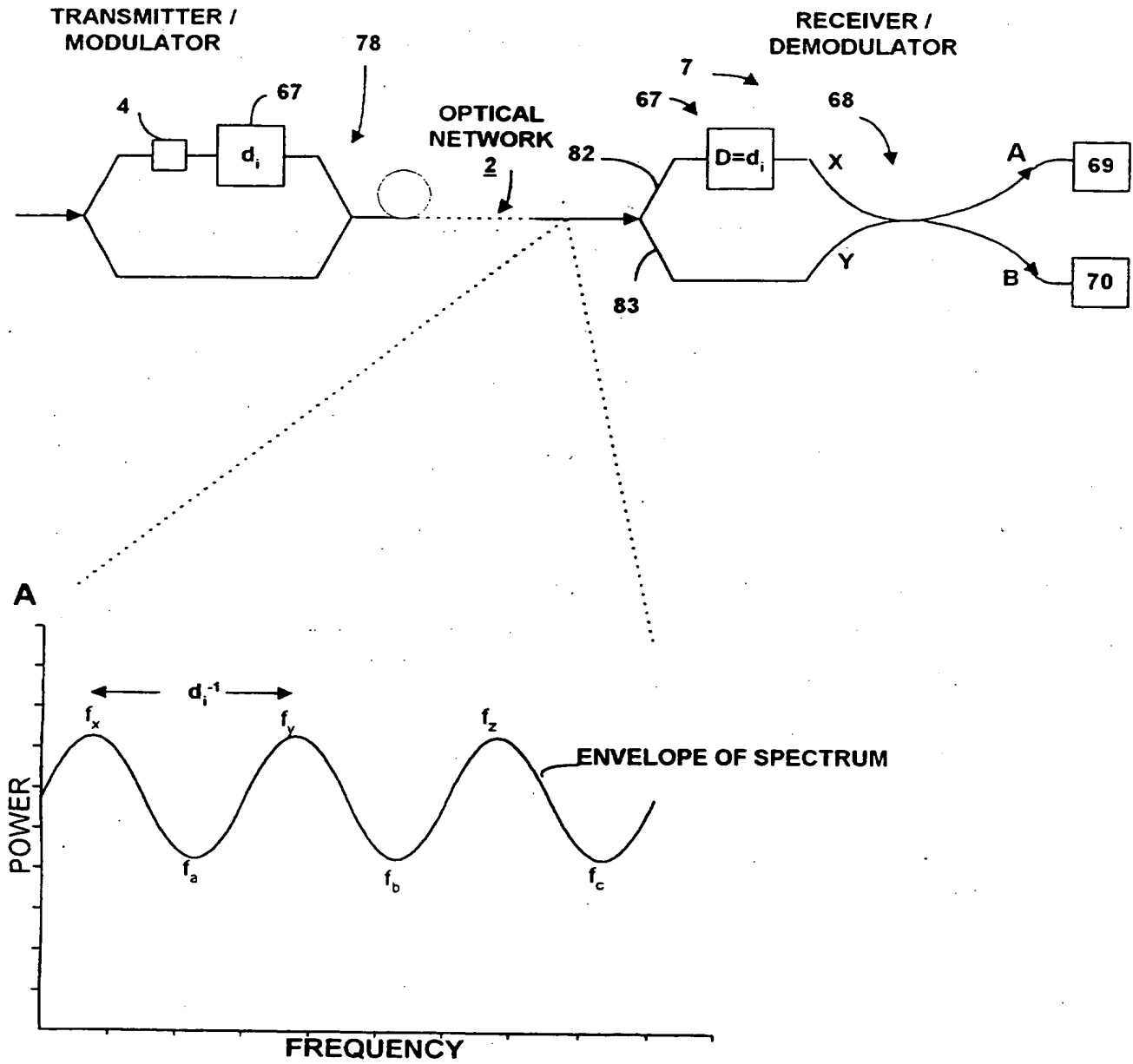
Fig 6B

DELAY ELEMENTS OF FOURIER  
MODULATOR

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Fig 7

FOURIER MODULATOR - SHOWING  
ONLY A SINGLE SPECTRAL  
MODULATION



NOT TO SCALE

Fig 8

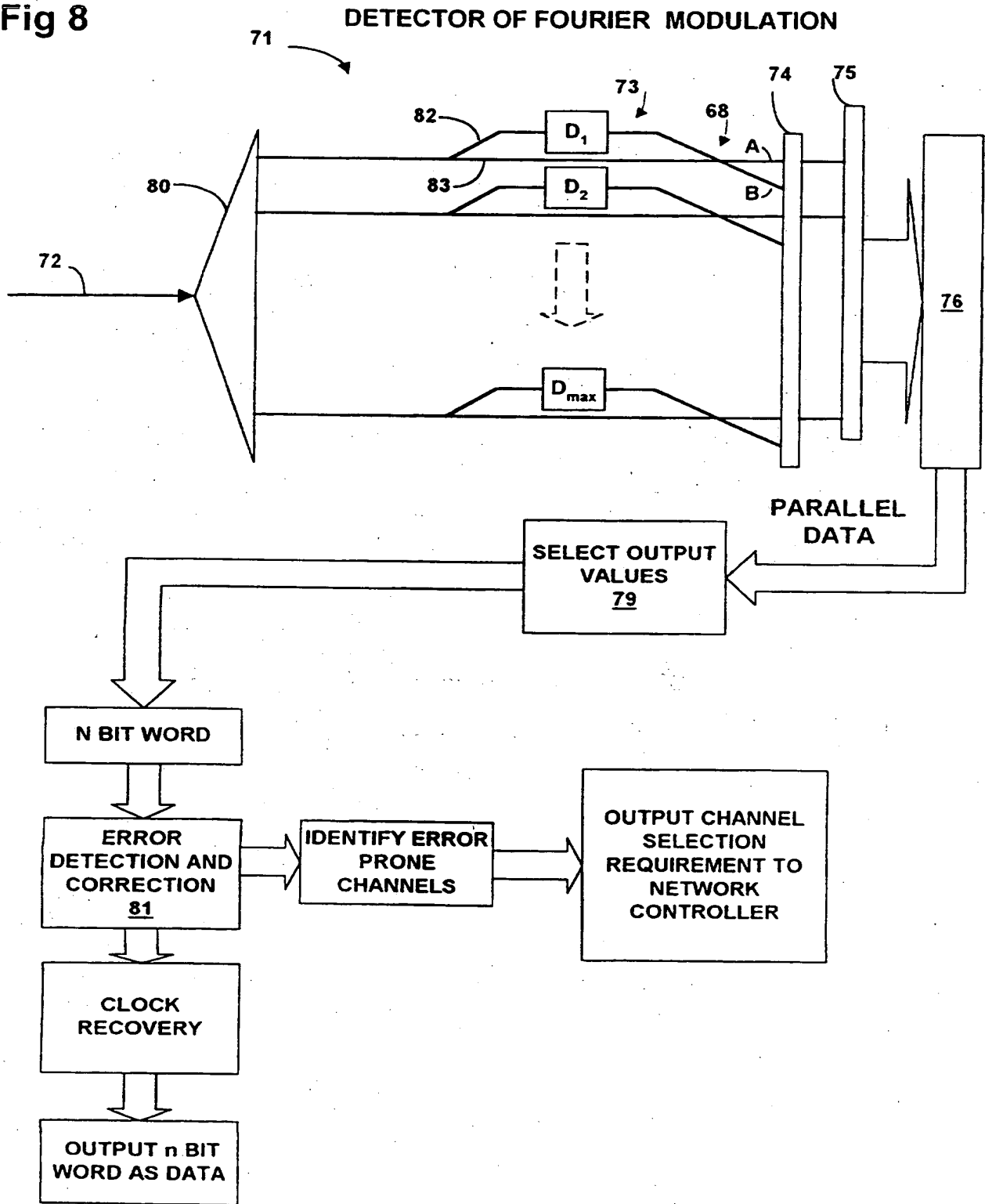
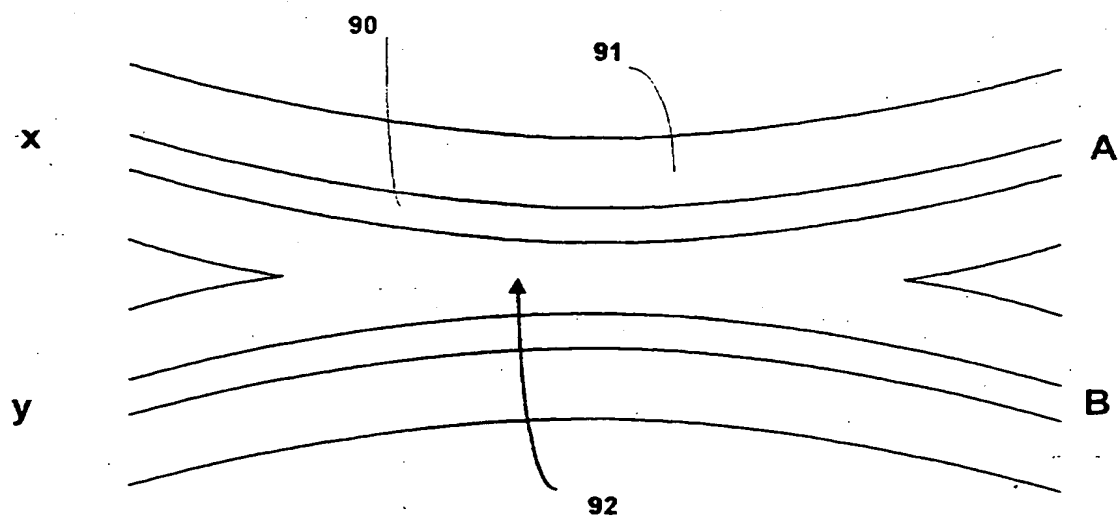


Fig 9

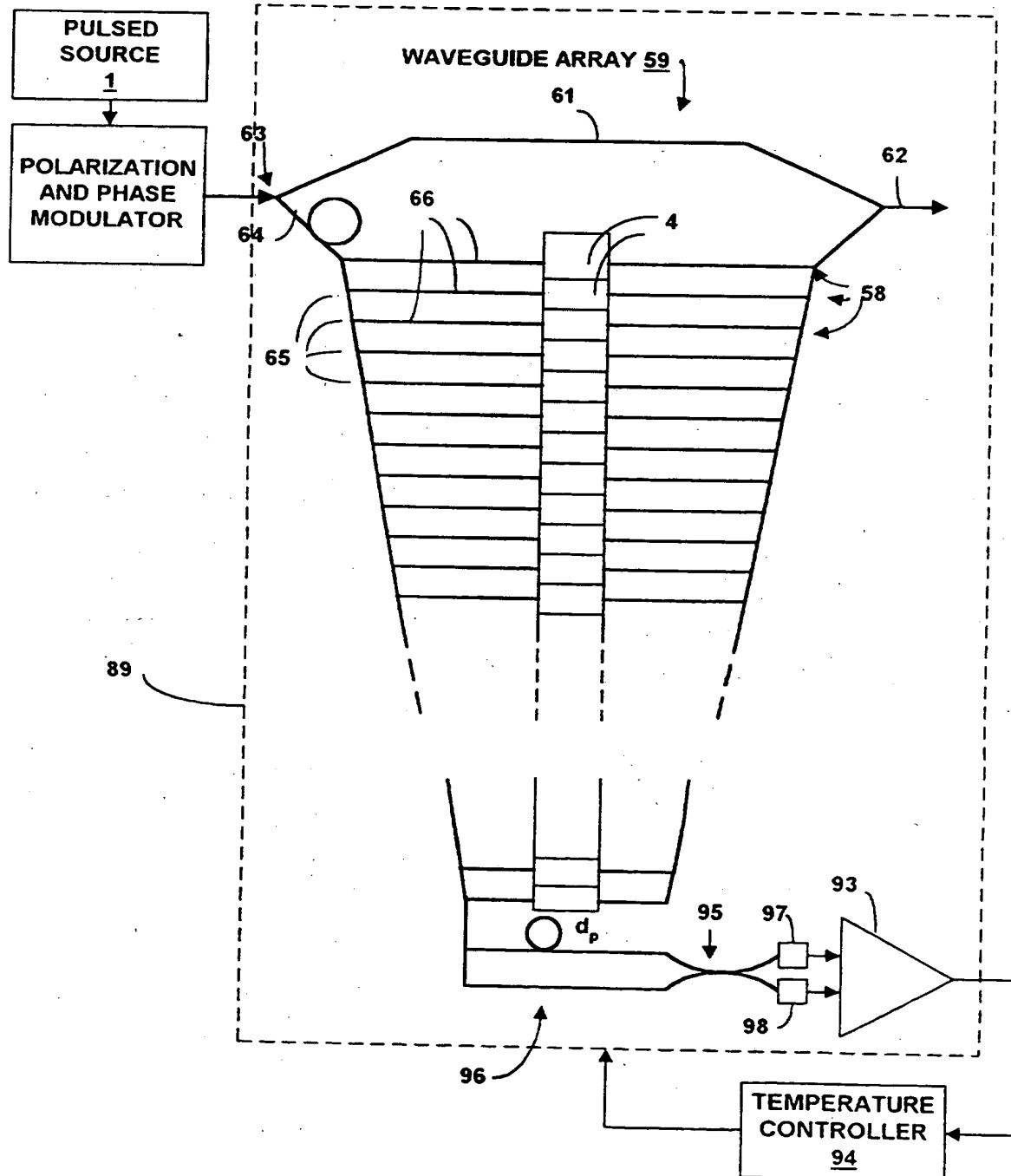
3 DB COUPLER



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Fig 10 A

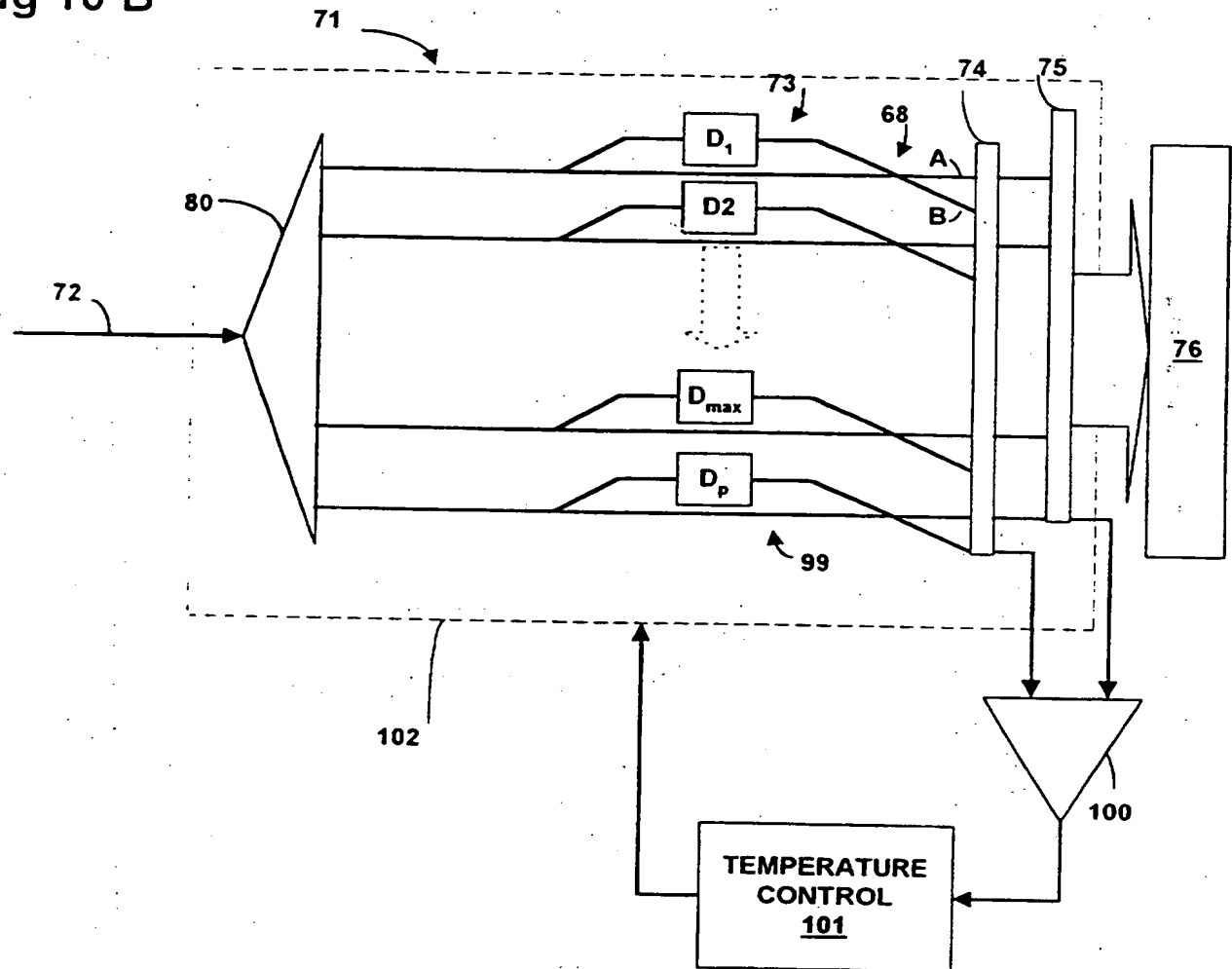
FOURIER MODULATOR  
WITH CONTROL TO PREVENT  
SYSTEMATIC DRIFT OF DELAY  
VALUES



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DETECTOR OF SPECTRAL MODULATION  
WITH CONTROL TO PREVENT SYSTEMATIC  
DRIFT IN DELAY VALUES

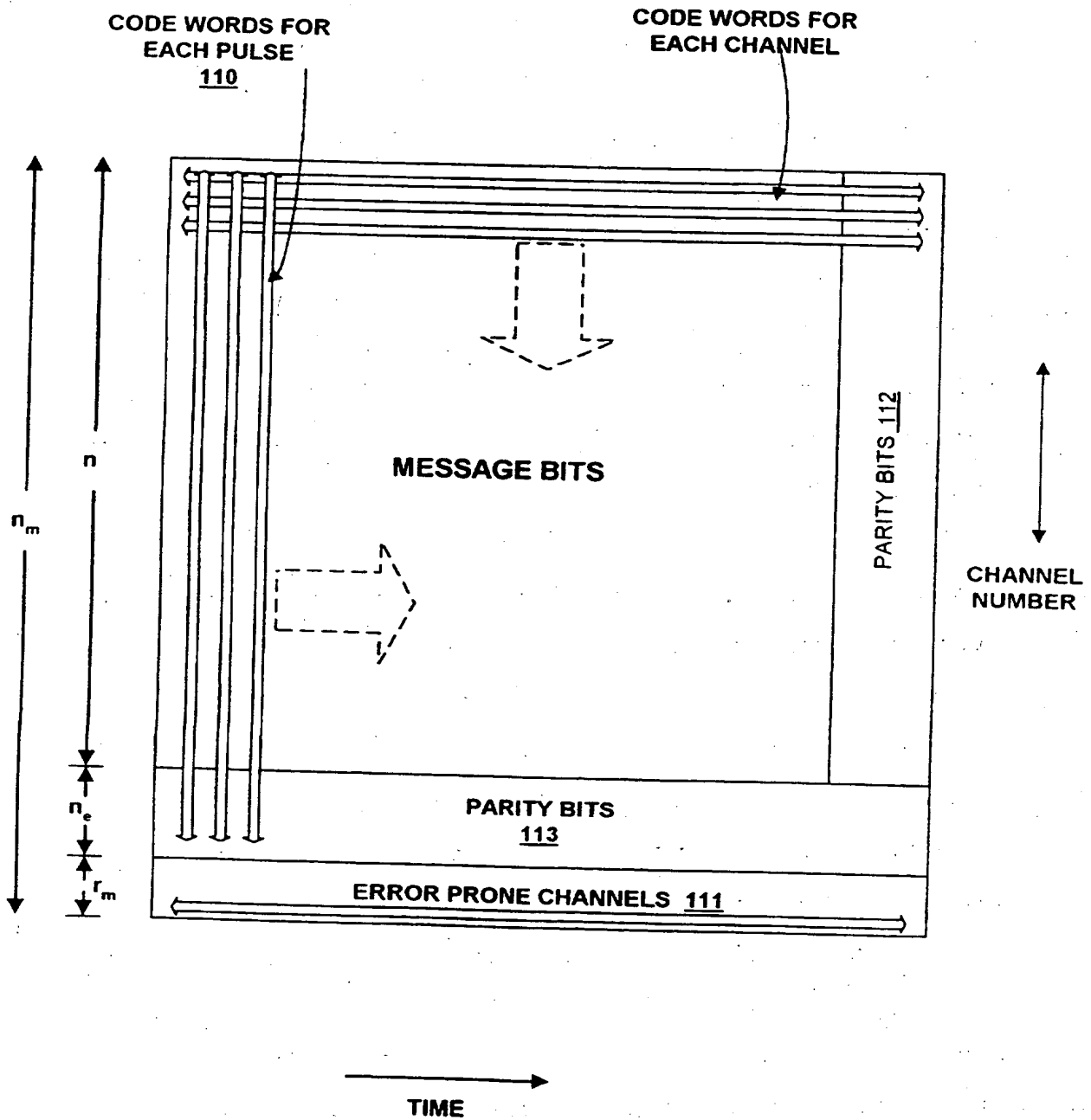
Fig 10 B



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Fig 11

ERROR CODING FRAME



C FLEGG 5250750

## MULTIPLEXED TRANSMISSION OF OPTICAL SIGNALS

This invention relates to high-capacity optical  
5 transmission systems in which each optical pulse is  
multiplexed to carry multiple bits of information.

Existing telecommunications systems typically transmit  
optical signals over optical fibres with a pulse rate of  
10 10 Gb/s and, for example, use wavelength division  
multiplexing to transmit eight channels simultaneously,  
thereby achieving a data rate of 80 Gb/s per fibre.  
Transmission of optical signals is possible over about  
400 km, using appropriate optical amplifiers, before  
15 conversion to the electrical domain is required to effect  
further regeneration.

It is estimated that future requirements of long distance  
traffic will require a transmission capacity greater than  
20 1 Terabit per second per fibre. This increase in  
performance cannot simply be accommodated in such systems  
by increasing the bit rate per channel because of the  
onset of non-linear effects such as self-phase modulation  
and because the associated electronic processing at  
25 increased serial data rates becomes prohibitively  
expensive. Similarly, increasing the number of channels  
per pulse presents difficulties. Currently each channel

is provided by a separate laser source whose output is filtered to a respective channel wavelength, the wavelengths being separated by guard bands to provide suitable tolerance to drifting due to environmental effects or ageing and, coupled with the limited bandwidth of laser amplifiers used for optical repeating systems, a limitation therefore exists on the number of channels which can be added to expand the data handling capacity of the system.

10

It is known from De Souza et al, Optics Letters vol. 20, no. 10, p.1166-8, to provide wavelength division multiplexing using a single broadband femtosecond source by slicing the spectral bandwidth into 16 channels which are modulated individually. De Souza proposes using a diffraction grating and collimating lens to disperse light from the source onto a modulator array chip and to recombine the component wavelengths into an output beam for transmission to a receiver. A disadvantage of this technique is the size of the diffraction grating and associated optics.

20

A similar arrangement is proposed by Knox et al in US-A-5526155 with the additional proposal that the diffraction grating could be replaced by a suitable wavelength splitter such as a Dragone wavelength router as described in C. Dragone, "An  $N \times N$  Optical Multiplexer Using a

25

Planar Arrangement of Two Star Couplers", IEEE Photonics Technology Letters, vol. 3, no. 9, pp812-815, September 1991. The Knox reference proposes that each channel is formed by many different longitudinal modes of the optical source, the output of a pulsed laser typically having a spectrum in which a series of closely spaced peaks, sometimes referred to as modes of the laser. It is proposed by Knox that 250 or more different channel signals may be generated in this manner to provide a transmission capacity of 25 Gbits/sec.

It is known from Shao et al, "WDM Coding for High-Capacity Lightwave Systems", Journal of Lightwave Technology, vol. 12, no. 1, January 1994, to provide error detection and correction coding in a wavelength division multiplexed optical system where  $n$  channels are provided by separate sources of respective wavelengths and parallel word transmission occurs such that  $n=k+r$  where  $k$  equals the number of data bits per word and  $r$  equals the number of parity bits per word. A Hamming coding scheme is utilised to define the calculation of parity bits and the data recovery process at the receiver.

According to the present invention there is disclosed a method of optical communication comprising the steps of;  
transmitting a train of optical pulses;

multiplexing each pulse to provide a plurality of channels; and

applying error correction coding to data carried by the channels using both interchannel coding and serial coding of individual channels.

Data transmission is thereby rendered more robust under a range of error conditions such as the onset of failure of one individual channel and also the occurrence of a burst of errors affecting a number of channels simultaneously.

Preferably the serial coding is enhanced by interleaving. BCH codes such as Hamming codes may conveniently be used.

According to a further aspect of the present invention there is disclosed a method of wavelength division multiplexing of optical signals for use in optical communications comprising the steps of;

generating optical signals by operation of a single laser source which is pulsed to have a spectral content comprising a series of spectral lines;

inputting the pulses to a dispersive device for spatially dispersing a set of the spectral lines for each pulse into respective output components, the dispersive device comprising an array of waveguides having a range of incrementally different lengths arranged in a phased

array configuration;

monitoring the extent to which the frequency selective properties of the waveguide array are matched to the spectral lines; and

5 controlling, in dependence upon the result of monitoring, the operation of at least one of the dispersive device and the laser source to maintain substantial uniformity with respect to time of the output components of the optical pulses.

10

The monitoring step preferably comprises monitoring the output of the waveguide array for a selected one of the spectral lines and controlling the operation of the dispersive device by regulating the temperature of a  
15 temperature controlled environment within which the waveguide array is located.

According to a further aspect of the present invention there is disclosed a method of optical communication  
20 comprising the steps of receiving optical pulses which are multiplexed to define a plurality of channels;

detecting the pulses to obtain temporally dispersed channel signals for the respective channels; and

generating clock signals for the respective channel  
25 signals for use in subsequent signal processing;

and wherein the generating step comprises extracting first and second clock signals in respect of first and

second channel signals, and determining clock signals for remaining channel signals by interpolation.

Conveniently the first and second channel signals are  
5 selected as the earliest and latest received of the channel signals respectively. The interpolation in a preferred embodiment is linear with respect to temporal dispersion.

10 According to a further aspect of the present invention there is disclosed a method of optical communication comprising the steps of;

transmitting a train of optical pulses; and

15 multiplexing each pulse to provide a plurality of channels;

the multiplexing step comprising;

modulating the spectrum of the pulse with a set of  
spectral modulations associated with respective channels  
such that a respective channel value for each channel is  
20 represented by an amount of corresponding spectral modulation, wherein each spectral modulation is defined by a respective characteristic of modulation as a function of frequency and wherein the characteristics are mutually orthogonal in frequency space.

25 Such spectral modulation (referred to below as Fourier modulation) may conveniently be in the form of sinusoidal

modulations in frequency space which may then be detected by Mach-Zehnder filters at a receiver.

Such spectral modulation enables the entire frequency  
5 content of the pulse to be utilised for each channel.

According to a further aspect of the present invention there is disclosed a method of optical communication comprising the steps of receiving optical pulses which  
10 are multiplexed to define for each pulse a plurality of channels such that a measurable parameter defining a property of the pulse has a first set of distinct values corresponding to respective channels;

detecting each received pulse by means of a detector  
15 array comprising detectors which are responsive to a second set of respective values of the parameter and which detectors output respective detector signals;

wherein the second set is greater in number than the first set so that the number of detector signals is  
20 greater than the number of channels;

and analysing the detector signals to extract channel signals representative of channel values carried by the respective channels.

25 The need for precise alignment of the detector array with any systematic drift in the measurable parameter is thereby avoided, as for example in the case of

multiplexing by wavelength division multiplexing where the measurable parameter is optical frequency and the detector array consists of detectors responsive to dispersed frequency components.

5

According to a further aspect of the present invention there is disclosed a method of optical communication comprising the steps of;

- transmitting a train of optical pulses;
- 10 multiplexing each pulse to carry a set of channels;
- receiving the optical pulses;
- monitoring for each channel a respective error rate in the received pulses;
- selecting on the basis of most favourable error rate
- 15 performance a subset of the set of channels to carry a first data stream;
- designating remaining channels on the basis of being relatively error prone as non-selected channels to carry a second data stream; and
- 20 wherein the first and second data streams comprise respective error detecting codes whereby the monitoring step determines the error rate performance therefrom.

Optimum performance from the system may thereby be

25 obtained by using the channels for which the rate of error detection is minimum.

The present invention also discloses communications systems and apparatus forming components of such systems for use in the above methods.

5 Preferred embodiments of the present invention will now be described by way of example only and with reference to the accompany drawings of which:

10 Figure 1 is a schematic diagram of an optical communications system with multi-channel multiplexing of pulses from a single optical source;

15 Figure 2 is a graphical representation of the spectrum of a pulsed laser source showing in curve A a general envelope of the source spectrum, in curve B detail of the peaks of the spectrum corresponding to laser modes, curve C showing the result of modulation and graph D showing the corresponding channels;

20 Figure 3 is a schematic representation of a wavelength splitter for use in the system of Figure 1;

Figure 4 is a schematic representation of a detector array;

25

Figure 5 is a schematic r presentation of a wavelength multiplexed system using a single pulsed source;

Figure 6A is a schematic diagram of a further embodiment of the present invention having a Fourier modulator;

Figure 6B is a schematic representation of the delay elements and multiplexing array corresponding to Figure

5 6A;

Figure 7 is a schematic representation of the encoding and decoding of a single channel of the Fourier modulator of Figure 6A;

10

Figure 8 is a schematic representation of a spectral modulation detector for use with the modulator of Figure 6A;

15 Figure 9 is a schematic drawing of a 3dB coupler as used in the detector of Figure 8;

Figure 10A is a schematic drawing of a Fourier modulator with temperature control;

20 Figure 10B is a schematic drawing of a detector of Fourier modulation with temperature control; and

Figure 11 is a schematic representation of a forward error correction scheme.

25

Figure 1 shows schematically a high-capacity optical transmission system in which optical pulses from a single

laser source 1 having a relatively broad bandwidth of 16nm are subject to a multiplexing process enabling each pulse to carry a large of number of channels. In the present context, the number of channels is used to denote  
5 signal carrying capacity of an optical network 2 over which the pulses are transmitted, and, typically, each channel can carry one bit of information per pulse. A data input 11 allows the input of a parallel n bit word, after suitable processing, to be encoded upon the optical  
10 pulse by means of the modulator array 5. Such processing may for example include error coding in a forward error coding unit 12 which adds the parity bits to the parallel word.

15 Pulses from the source 1 are divided by a splitter 3 in a manner suitable for presentation to modulating elements 4 of a modulator array 5. One possible example of a splitter 3 would be a wavelength dispersive element as described below with reference to Figure 3 for spacially  
20 separating the pulse into components having distinct respective wavelengths. The splitter 3 however in its general context is not limited to such wavelength division multiplexing methods and could for example comprise simple division into components of equal  
25 amplitude for presentation to modulating elements 4 which apply respective distinct phase modulations as described below with reference to Figures 6 to 8.

Components of the optical pulse modulated by the modulator array 5 are recombined in combiner 6 and are output to the optical network 2 to be received at a remote location where an analyser 7 divides the received pulse for presentation to a detector array 8. Electrical outputs 9 from detecting elements of the detector array 8 are input to a processor 10 which interprets the electrical outputs to recover the  $n$ -bit word for subsequent processing including retiming by means of clock recovery circuit 16.

The system includes a degree of redundancy in the number of channels capable of carrying user data and also provides error detection and correction in order to allow for the occurrence of occasional bit errors or varying degrees of failure of individual channels. Input data is formulated as parallel words of  $n$  bits where in the present example  $n = 1014$ . The data input word is error coded using a BCM (Bose-Chaudhuri-Hocquenghem) code and the resulting code word of  $N=n+n_e$  bits is transmitted to the modulator array, thereby allowing the entire code word to be transmitted in a single pulse. The number of modulating elements forming the modulator array 5 is therefore required to be greater than  $n + n_e$  where  $n_e$  is equal to the number of parity bits added by the error coding. The number  $n_e$  of modulating elements is chosen

to provide a degree of redundancy such that

$$n_m = n + n_e + r_m = N + r_m$$

- 5 where  $r_m$  is a number of redundant channels available in the modulator array 5. (The term 'redundant' is, in the present context, used to indicate that these channels are not selected to carry user data. The 'redundant' channels may however be used for other purposes.) The
- 10 provision of such redundant channels at the transmitter therefore allows  $N$  channels to be selected from  $n_m$ , leaving up to  $r_m$  channels to be designated as error prone channels should any be identified as such.
- 15 Similarly, at the receiver, a degree of redundancy is provided. A number  $R$  of redundant channels available at the detector is accommodated by increasing the number of detector elements 10, the number  $R$  being greater than  $r_m$  to allow for systematic errors and drift occurring over
- 20 time in the manner of transmission via the optical network 2. In order to avoid the need for precise alignment relative to the received signals or modulating elements 4, the number of detecting elements 10 is further doubled to provide interleaving or intermediate
- 25 detecting elements so that for example, where a series of parameters  $d_i$  define the distinguishing characteristic

between channels, intermediate detection elements are provided to respond to values  $d'_i = d_i + \frac{1}{2}(d_{i+1} - d_i)$ .

Consequently,  $n_d = 2(n_m + R)$  detection elements 10 are provided and are connected to a processor 13 which receives the resulting  $2(n_m + R)$  inputs, the processor interpreting the inputs and outputting  $N = n + n_e$  channel signals as a parallel word. Typical values required to achieve 1Tb/s with a pulse rate of nominally 1GHz are  
 10  $n = 1014$ ,  $n_e = 10$  and  $R = 10$ .

An example of forward error correction for use in the present embodiments is a block code of the BCH (Bose, Chadhuri, Hocquenghem) type where the number of parity  
 15 bits required depends upon the number of errors per code word for which the coding system is capable of providing correction. For most applications, a Hamming single error correcting code will be sufficient. The typical values referred to above for  $N$  and  $n_e$  correspond to a  
 20 Hamming code.

Figure 11 shows schematically the manner in which encoded bits may be framed where forward error correction is utilised. For each time sample,  $n$  message bits are  
 25 encoded by interchannel coding to provide  $n_e$  parity bits 113 and transmitted as code words 110 having  $n+n_e$  channel

bits. The diagram of Figure 11 shows the framing of user data channel bits together with redundant or error prone channel bits 111 associated with the excess number of modulating elements. (For convenience, the error prone channels are shown schematically in a common block.) For each time frame in a given user data channel, further forward error correction is performed by serial coding to provide additional time frame parity bits 112, the resulting code words 114 thereby providing for each channel an additional mechanism for correcting errors. If for example errors are confined to a single channel, the error correction in the "vertical direction" of Figure 11 for a single sample time is capable of correcting the single error and this process will be repeated at successive sample times. If on the other hand a series of errors occur at a single sample time in more than one channel, error correction using the time frame parity bits 112 is capable of correcting these errors by correction of a single error bit in each one of the code words 114.

In order to allow for error correction of more extensive burst errors covering more than one channel and more than one adjacent time slot, the technique of data interleaving may be utilised so that bits from adjacent time samples belong to different error correcting frames.

An error detection and correction unit 81 as shown in Figure 1 extracts the  $n$  bit word of data and, in the process of doing so, identifies error prone channels by statistical analysis of the results of error detection.

- 5 The use of such error prone channels for communicating user data is avoided by outputting a selection requirement to a network controller 14 which activates a channel selection control circuit 15 to reallocate the channels used by the modulating elements 4 for user data.
- 10 The error prone channels are then accommodated within the  $r_m$  redundant channels 111 provided in the modulator array 5.

- Those channels which are identified as error prone are
- 15 then used to carry an error detecting code which is detected and monitored in order to assess the performance of the channel over time. If for example the performance of a given error prone channel improves whereas other channels currently carrying user data deteriorate, the
- 20 designation of redundant error prone status can be changed in order to continually utilise for user data those channels likely to provide the best performance.

- In a preferred embodiment, a channel which has been
- 25 designated as being an error prone channel must improve its performance in terms of error rate by a factor of 10 times better than the next candidate channel before

losing the designation of being error prone so as to return to use in communicating user data. The assessment of error rate in an error prone channel in a preferred embodiment requires an error count to be accumulated for  
 5 5 milliseconds in hardware, the accumulated values then being read by the controller 14.

More generally, the above process may be regarded as selecting a subset of the available channels to carry a  
 10 first data stream on the basis of most favourable bit error rate performance, the first data stream consisting of code words which include the user data. Remaining channels are designated as being non-selected channels carrying a second data stream, also carrying error  
 15 detecting code. The non-selected channels may still carry user data if required although preferably at a lower bit rate or alternatively using an error correction code capable of correcting a greater number of errors.

20 The channels will generally be coded with binary data but may also carry non-binary coding, such as in the case of duo-binary signalling, and in this case a non-binary BCH code such as a Reed-Solomon code.

#### 25 WDM Method:-

A first example of a modulation and demodulation method will now be described with reference to Figure 5, the

method being one of wavelength division multiplexing (WDM). The system of Figure 5 corresponds broadly to the system of Figure 1 and omits some detail such as error correction for clarity.

5

Figure 2 shows graphically at curve A the envelope of the spectrum of a pulse laser source, the detailed fine structure being shown at graph B to comprise a series of modes which are equispaced in frequency by a frequency interval  $f_d$  which is equal to the pulse rate at which the laser source 1 is pulsed. In this example, adjacent modes are selected as available channels in the modulator array 5 and the laser source is pulsed at 2 GHz. A typical output of the wavelength combiner 6 of Figure 5 is illustrated in graph C of Figure 2, corresponding to transmitted bits shown in graph D, and showing the effect on spectral line shape due to modulation.

10  
15

20

25

Figure 3 shows schematically a wavelength dispersive element for spacially dividing the pulse into wavelength components  $f_1$  to  $f_m$ , thereby constituting an embodiment of the splitter 3 of Figure 5, based on a wavelength routing device proposed by C. Dragone, as referenced above. In Figure 3, each heavy solid line represents a waveguide.

The wavelength routing device 30 of Figure 3 is based on

a star coupler 31 and an optical waveguide array 32 in the form of a series of waveguides 33 defining respective optical path lengths which differ incrementally from one another. Each of the waveguides 33 has a respective  
5 input/output end 34 defining a part circular boundary of a free space region 35 and each has a free end 36 terminating in a respective reflector.

Optical pulses from the source 1 are input to the free  
10 space region 35 via an input waveguide 37 and a set of output waveguides 38 have their free ends 39 presented to the free space region 35 so as to receive outputs dispersed spacially from the waveguides 33 according to their wavelengths. The waveguide array 32 therefore may  
15 be regarded as being equivalent to a grating used for spacial dispersion of wavelengths.

Figure 3 is to be regarded as schematic and representing only a limited number of both output waveguides 38 and  
20 grating waveguides 33, the number of output waveguides 38 in practice corresponding to the number of frequencies required and the number of array waveguides being typically at least four times the number of output waveguides.

25

The wavelength routing device 30 has a spectral response which is accurately aligned to the spectrum of the laser

source 1 so as to act as a filter having a response represented by peaks of the spectrum shown in Figure 2 Graph B. The filter is temperature-tuned to the source 1 by means of placing the filter in a temperature controlled environment and controlling the temperature using a feedback loop driven by a measure of the match in frequency between the filter and source characteristics. A suitable method of providing such measurement is to utilise a spectral line at one end of the source spectrum and a corresponding output of the filter to a detector. In the wavelength multiplexed system illustrated schematically in Figure 5, temperature tuning of the source 1 is represented schematically by a monitor circuit 49 which provides an input to a temperature controller 48 which controls the temperature environment of the wavelength splitter 3.

After transmission through the optical network 2, each received pulse is divided into separate wavelength components by the analyser 7 which may for example be a waveguide array of the type shown in Figure 3 and in which the wavelength dispersed output is directed onto a detector array 8 as shown schematically in Figure 4 in which the spectral power falling onto the detector array is illustrated graphically in graph A. The detector array 8 comprises an array of detector elements 10 of which the number  $n_d$  of detector elements 10 is more than

double the number of channels to be detected in order to allow for systematic drift in the position at which the signals are dispersed onto the detector array 8. Each peak in the spectrum will generally be detected by two adjacent detector elements 10. An alignment processor 40 receives the output signals from each of the detector elements 10, combines the output from each pair of detector elements 10, and maps the output onto binary values of transmitted channels.

10 In the presence of frequency drift, the power distribution in graph A of Figure 4 will move to one side as represented by the broken line graph and the outputs from the individual detector elements 10 will vary such that each wavelength peak will still be detected by two adjacent detector elements although with different proportions being detected by each of the pair. The output alignment processor is invariant to such drift.

20 By such an arrangement, the need for repeated calibration or active tracking control to achieve precise alignment of the detector array 8 is avoided.

The wavelength components of a pulse are likely to be subject to differential delay, such wavelength dependent (temporal) dispersion being increasingly problematic with increasing transmission distance. The (temporal)

dispersion is at least partially compensated optically by transmission through a (temporal) dispersion compensating system 52. Some residual (temporal) dispersion is however likely to remain. Clock recovery  
5 of the individual wavelength channels may generally therefore require each channel to be provided with an individual clock recovery circuit.

In the present example, however, clock recovery is  
10 simplified by an interpolation technique as illustrated schematically in Figure 5. Clock recovery signals 50 and 51 are sampled from the earliest and latest received output channels C1 and CN which corresponds to the maximum and minimum frequencies at which data is  
15 transmitted. In the preferred embodiment, C1 and CN are channels dedicated to only carry clock signals. The phases of clocks required for each of the intermediate data channels C2 to CN-1 is then obtained by interpolation of the phases detected for each of these  
20 extreme clock signals. The interpolation is linear in the preferred embodiment but, if necessary, a non-linear interpolation could be effected where appropriate. Individual clock signals are derived by adding together  
25 weighted versions of the sinusoidal clock signals derived from the C1 and CN channels, the weights being varied linearly or non-linearly as required.

In Figure 5, the (temporal) dispersion compensation system 52 is adaptively controllable and is controlled by a control signal derived from processing the clock recovery signals, as illustrated schematically by  
5 (temporal) dispersion compensation control processor 53.

In Figure 5, a phase interpolation circuit 56 receives clock recovery signals from clock recovery circuits 54  
10 and 55 and by a process of interpolation derives appropriately phase shifted clock signals for each of the channels C2 to CN-1, the clock signals being output to retiming circuits 57 which include, for each of these channels, a retiming D-type flip-flop. Retimed data  
15 output is thereby produced as a parallel word, subsequently processed for error detection and correction as described above with reference to Figure 1.

#### Fourier Modulation Method

20 A second example of multiplexing in an optical transmission system of the type described above with reference to Figure 1 will now be described. Figure 6A illustrates a method of modulating a single optical pulse to carry a large number of channels by a spectral  
25 modulation technique which is alternatively referred to herein as Fourier modulation. Unlike the above described wavelength division multiplexing technique, the Fourier

modulation technique encodes the optical pulse such that each channel utilises a broad bandwidth of the pulse i.e. a large number of the modes of Figure 2, Graph B, the same bandwidth being available to each of the channels, and the channels being associated with respective periodic modulations in frequency space of the spectrum of the transmitted pulse. The term modulation in this context implies a characteristic imposed into the envelope of the spectrum of the optical pulse and which is generally time invariant for the duration of the pulse (as described below with reference to Figure 7A).

A periodic modulation of the spectrum with a specific period in frequency space may for example be achieved using a Mach Zehnder interferometer in which mutually coherent samples of the pulse are recombined after introducing a delay  $d_1$  in one component, the resulting modulation in frequency space being a sinusoid having a periodicity expressed as a frequency increment equal to the inverse of the delay.

The Fourier modulator 60 of Figure 6A will be described using corresponding reference numerals to those of preceding Figures where appropriate for corresponding elements. Pulses from a pulsed optical source 1 are input to a waveguide array 59 in which a reference waveguide 61 communicates with an output waveguide 62 so

s to introduce a delay  $d_r$ . At the input to the reference waveguide 61, a 3dB splitter 63 divides one half of the power in the pulse into a waveguide 64 leading to a splitter 65 which in turn diverts a portion of the signal power into a respective delay waveguide 66. Successive 30dB splitters 65 similarly divert signal power into respective delay waveguides 66, the length of the delay waveguides 66 being mutually different and increasing incrementally by  $S$  in the array to define a series of time delays  $d_i$  where

$$d_1 = 2d_r$$

$$d_2 = 2d_r + \delta$$

$$d_3 = 2d_r + 2\delta$$

$$\vdots \quad \vdots \quad \vdots$$

For example,  $D = 512$  p sec and  $\delta = 0.5$  p sec to provide 1024 different values of  $d_i$ . Each of the delay waveguides 66 communicates with a respective modulating element 4 of a modulator array 5 which, in the example of Figure 6A, is illustrated schematically as a transmission type modulator. The optical pulse components conducted through the delay waveguides 66 emerge from the modulator elements 4 and are recombined with the remainder of the pulse transmitted via the reference waveguide 61 using appropriate couplers 58.

Actuation of each of the modulating elements 4 thereby

allows a distinct spectral modulation to be introduced into the optical signal within the pulse which is output via the output waveguide 62.

- 5 The pulses are introduced to the array via polarization and phase modulators 68 which act to invert the optical phase of each successive pulse and shift the polarization by 90 degrees between successive pulses. These measures reduce the likelihood of coherent addition between
- 10 successive pulses. The nature of the spectral modulation is explained schematically in Figure 7 in which a spectral modulation unit 78 in the form of a Mach Zehnder interferometer performs spectral modulation which is detected by an analyser 7 in the form of a Mach-Zehnder
- 15 filter and where in each case a delay  $d_i$  is represented by a respective delay element 67. Division and recombination after introducing a delay into one arm of the interferometer 78 as shown in Figure 7 results in a modulation of the spectral content of the pulse. This
- 20 modulation is illustrated schematically in graph A of Figure 7 which shows a generally sinusoidal modulation in frequency space of the power, peak power being shown at a series of frequencies  $f_x, f_y, f_z, \dots$  and minimum power being shown at a series of frequencies  $f_a, f_b, f_c, \dots$ .
- 25 The periodicity of this modulation in frequency space is determined by the value of  $d_i$  (the frequency interval

between peaks =  $(d_i)^{-1}$ ) and frequencies  $f_x, f_y, f_z, \dots$  are frequencies for which a phase difference between the outputs of the two arms of the interferometer is an even multiple of  $\pi$ , thereby giving constructive interference.

5 Frequencies  $f_a, f_b, f_c, \dots$  are frequencies for which a phase difference between the outputs is an odd multiple of  $\pi$ , thereby giving destructive interference. Where a series of interferometers with distinct values of  $d_i$  are provided as in the case of the waveguide array of Figure  
10 6A, a set of distinct, orthogonal modulations in frequency space are possible. Figure 6B shows schematically a representation of the delay waveguides 66 of Figure 6A using the delay element notation of Figure 7. The summation of these distinct sinusoidal  
15 modulations in frequency space may be regarded as constituting a Fourier series and hence the spectral modulation may be termed Fourier modulation in the present context.

20 Each of the delay elements  $d_i$  is shown in Figure 6B in series with a respective modulating element 4 so that the associated modulation is only present in the output signal when the respective modulator element 4 is activated to allow conduction of the optical signal and  
25 allow interference to occur. The delay elements  $d_i$  are arranged in parallel, thereby avoiding mechanical issues

i.e. difficulties of construction.

Detection in the received output at the analyser 7 of Figure 7 makes use of a property of a 3dB coupler 68 which receives inputs X and Y and delivers outputs A and B to detector elements 69 and 70 respectively. A 3dB coupler is illustrated in Figure 9 in which two waveguides are brought into close proximity such that waveguide cores 90 are sufficiently close to allow an exchange of radiation to occur, in dependence upon the length of interaction region 92 common to the cladding 91 of each waveguide.

A property of the 3dB coupler 68 is that, for coherent inputs X and Y, the inputs will be coupled into the outputs in a manner such that the distribution of power in the outputs A and B is generally dependent upon the relative phase of the inputs X and Y. Consequently, a 3dB coupler may be configured such that any components of a particular frequency which are mutually in-phase for the inputs X and Y will be output to A and detected by the detector 69 of Figure 7 whereas components which are out of phase will be output to B and detected by detector 70. In the example shown, components of frequency  $f_x, f_y, f_z, \dots$  will appear in-phase when analysed using a Mach-Zehnder filter having a delay  $D = d_1$  since by definition these frequencies correspond to a phase

difference which is an even multiple of  $\pi$  for delay  $d_i$ . These frequency components will be coupled to the detector 69. Frequencies  $f_a, f_b, f_c, \dots$  however will appear as out of phase components of X and Y since by definition  
 5 these frequencies correspond to a phase difference which is an odd multiple of  $\pi$  for a delay of  $d_i$  and will be coupled to detector 70.

The relative strengths of the in phase components  $f_x, f_y, f_z, \dots$  and out of phase components  $f_a, f_b, f_c, \dots$  will  
 10 vary according to whether the pulse is spectrally modulated with delay  $d_i$ . The value of the differential output between detectors 69 and 70 can therefore be used to detect spectral modulation.

15 A spectral modulation detector 71 for detecting  $2(n_m + R)$  different spectral modulations is shown schematically in Figure 8. Each pulse is received via an input waveguide 72 connected to a signal splitter 80 which divides and  
 20 then amplifies the signal equally to be directed to a set of Mach-Zehnder filters 73. Each Mach-Zehnder filter 73 corresponds to the analyser 7 of Figure 7 in which the pulse is divided into respective first and second arms 82 and 83 and transmission via the first arm subjected  
 25 to time delay  $D_i$  before recombining in a 3dB coupler 68, the outputs A and B of which are connected to separate

detectors. In the spectral modulation detector of Figure 8, first and second PIN diode arrays 74 and 75 are used to detect the respective outputs A and B from each of the Mach-Zehnder filters 73 and the differential outputs for each signal component are processed by a differential amplifier array 76.

Each of the Mach-Zehnder filters 73 is tuned to provide a respective delay  $D_i$ , the values of the delays  $D_i$  being selected to include values corresponding to each of the delays  $d_i$  to  $d_m$  used in the modulators of Figure 6. For each instance of activation of a modulator 4, represented by closure of one of the switches 77 of Figure 6B, a characteristic spectral modulation of period  $d_i^{-1}$  in frequency space will be encoded into the spectrum of the pulse as illustrated in Graph A of Figure 7 and this will be detected in the Mach-Zehnder filter 73 having the corresponding delay  $D_i$  to produce a differential output. A parallel data word output from the differential amplifier array 76 will therefore be modulated accordingly. As in the case of the first example using WDM, the spectral modulation detector of Figure 8 includes a degree of redundancy in that it comprises a number of Mach-Zehnder filters 73 which is more than twice the number of spectral modulation units 78 at the transmitter, the respective delay values  $D_i$  at the

detector comprising a set of  $m$  values equal to those of the spectral modulator 60 plus a set of  $m$  intermediate or interleaved values as well as  $R$  redundant values at the maximum and minimum extent of  $d_i$ .

5       Systematic errors occurring at the time of construction or appearing over time may therefore be accommodated by suitable signal recovery by inputting the data to a processor 79 operable to select output  $n_m$  values of the  
10       transmitted word. Subsequent error detection and correction is carried out by a processor 81 to extract the  $n$  bit word of user data.

15       In the above examples, a 1024 bit word is modulated onto each pulse using a pulse repetition rate of nominally 1GHz in order to achieve a data carrying capacity of the order of 1Tb/s. Transmission may be by a single optical fibre with corresponding multiplexed data transmission operating in both directions. Optical pulse generation  
20       consists of generating a very narrow pulse which is then dispersed so as to fill most of the bit period in order to reduce peak power. The reduction in peak power has the advantage of avoiding non-linearities during transmission via optical fibres.

25       In the above described embodiment utilising Fourier modulation, the number of delay waveguides 66 is 1034 of

which 10 represent redundant channels. The corresponding values of delay elements 67 are separated by increments of 0.5ps over the range 517 to 1,033.5ps. The nominal 1GHz pulse rate is more precisely given as the inverse of the bit period i.e.  $(1,034 \cdot 10^{-12})^{-1}$ .

In the embodiment of Figure 5, wavelength matching of the filter (wavelength splitter 32) is achieved by temperature control of the filter. Alternatively, wavelength matching may be achieved by regulating the pulse repetition rate of the source 1 in order to thereby variably control the values of the laser mode frequencies and the frequency spacing  $f_d$  between mode frequencies  $f_1, f_2, f_3, \dots$ . At the receiver, detection of the pulse rate enables the receiving electronics to adapt to wavelength variation.

Alternatively, using the method of temperature controlling the filter, the degree of matching between the source and filter response may be detected by sensing the power coupled to the modulator by for example sensing the bias current supplied to the modulator.

In the embodiment of Figures 6 to 9 which utilise Fourier modulation, the effects of drift are accommodated by the use of interleaved delay elements at the receiver

responsive to intermediate values of delay  $D_1$ . A further arrangement is shown in Figure 10A has an analyser 96 (i.e. a Mach Zehnder filter) of the type shown in Figure 7 added to the waveguide array 59 of the modulator of Figure 6A for the purpose of tracking systematic drift in the delay parameter  $d_1$ . This tracking analyser 96 has a value of delay  $d_p$  matched to the pulse repetition rate of the source 1 such that  $f_d = d_p^{-1}$ . The analyser 90 has a 3dB coupler 95 at its output, connected to detecting elements 97 and 98 and a differential amplifier 93 detects a difference signal from the outputs of the detecting elements.

The output of the tracking analyser 96 is sensitive to the degree of correspondence between the value of the delay  $d_p$  and the inverse of the frequency interval between laser source modes  $f_d$ . A maximum output is therefore obtained when  $d_p = f_d^{-1}$  and any departure from this coincidence follows a sinusoidal characteristic.

A temperature control circuit 94 provides regulation of a temperature controlled environment 89 within which the waveguide array 59 is located so as to maintain maximum output of the differential amplifier 93. Since the values of delay are sensitive to temperature, this provides a mechanism for maintaining matching performance of laser source 1 and waveguide array 59.

A similar control mechanism may be utilised at the receiver as shown in Figure 10B where an additional analyser 99 has a delay  $D_p$ . Differential outputs from the analyser 99 are amplified by differential amplifier 100 and used in a feedback loop to drive a temperature control 101 which regulates a temperature controlled environment 102 containing the waveguide array 71.

Alternative embodiments are envisaged in which for example the transmission type modulating elements of Figures 1 and 5 are replaced by reflection type modulating elements. Similarly, the Dragone wavelength router of Figure 3 may be configured to utilise a wavelength array grating in which light is conducted to a further star coupler instead of utilising the reflectors provided at the free ends 36.

The embodiment of Figure 5 using WDM may alternatively utilise alternate laser mode frequencies to provide guard bands between selected modes. Conventional spectral reduction techniques such as partial response coding may also be used. Duobinary coding may for example be employed, using a modulation technique which encodes the signal at three possible levels or states, providing the transmitter with appropriate precoding circuitry for each channel and providing the receiver with appropriate decoding circuitry for each channel.

CLAIMS

1. A method of optical communication comprising the steps of;

transmitting a train of optical pulses;

5 multiplexing each pulse to provide a plurality of channels; and

applying error correction coding to data carried by the channels using both interchannel coding and serial coding of individual channels.

10

2. A method as claimed in claim 1 wherein said interchannel coding provides for each pulse a code word consisting of bits carried by the plurality of channels, said bits comprising user data bits and parity bits.

15

3. A method as claimed in claim 2 wherein said serial coding comprises the formation of code words for respective individual channels, each code word comprising a series of said user data bits from different pulses and from the individual channel and further parity bits applying error correction coding thereto.

20

4. A method as claimed in claim 3 wherein the serial coding provides code words consisting of user data bits from non-successive optical pulses such that said code words are interleaved.

25

5. A method as claimed in any preceding claim wherein at least one of said interchannel coding and said serial coding comprises a BCH code providing correction of multiple errors per code word.

5

6. A method as claimed in any preceding claim wherein said interchannel coding comprises a Hamming code.

7. An optical communication system comprising;

10 a transmitter operable to transmit a train of optical pulses;

multiplexing means operable to multiplex each pulse to provide a plurality of channels; and

15 encoding means operable to apply error correction coding to data carried by the channels using both interchannel coding and serial coding of individual channels.

8. A system as claimed in claim 7 wherein said 20 interchannel coding provides for each pulse a code word consisting of bits carried by the plurality of channels, said bits comprising user data bits and parity bits.

9. A system as claimed in claim 8 wherein said serial 25 coding comprises the formation of code words for respective individual channels, each code word comprising a series of said user data bits from different pulses and

from the individual channel and further parity bits applying error correction coding thereto.

10. A system as claimed in claim 9 wherein said encoding  
5 means comprises interleaving means operable such that the serial coding provides code words consisting of user data bits from non-successive optical pulses whereby said code words are interleaved.

10 11. A method as claimed in any of claims 7 to 10 wherein at least one of said interchannel coding and said serial coding comprises a BCH code providing correction of multiple errors per code word.

15 12. A method as claimed in any of claims 7 to 11 wherein said interchannel coding comprises a Hamming code.

13. A method of wavelength division multiplexing of optical signals for use in optical communications  
20 comprising the steps of;

generating optical signals by operation of a single laser source which is pulsed to have a spectral content comprising a series of spectral lines;

inputting the pulses to a dispersive device for  
25 spatially dispersing a set of the spectral lines for each pulse into respective output components, the dispersive device comprising an array of waveguides having a range

of incrementally different lengths arranged in a phased array configuration;

monitoring the extent to which the frequency selective properties of the waveguide array are matched  
5 to the spectral lines; and

controlling, in dependence upon the result of monitoring, the operation of at least one of the dispersive device and the laser source to maintain substantial uniformity with respect to time of the output  
10 components of the optical pulses.

14. A method as claimed in claim 13 wherein the monitoring step comprises monitoring the output of the waveguide array for a selected one of the spectral lines  
15 and controlling said operation so as to maximise said output.

15. A method as claimed in any of claims 13 and 14 wherein the controlling step controls the dispersive  
20 device by regulating the temperature of a temperature controlled environment within which the waveguide array is located.

16. A method as claimed in any of claims 13 and 14  
25 wherein said controlling step regulates the operating frequencies of the laser source.

17. A method as claimed in any of claims 13 to 16 wherein the frequency selective properties of the waveguide array are matched to the series of spectral lines from the laser source.

5

18. Multiplexing apparatus for wavelength division multiplexing of optical signals for use in optical communications comprising;

a laser source for generating optical signals;

10 means for pulsing the laser source such that the laser source has a spectral content comprising a series of spectral lines;

a dispersive device operable to spatially disperse a set of the spectral lines for each pulse into  
15 respective output components, the dispersive device comprising an array of waveguides having a range of incrementally different lengths arranged in a phased array configuration;

monitoring means operable to monitor the extent to  
20 which the frequency selective properties of the waveguide array are matched to the spectral lines; and

control means operable to control, in dependence upon the result of monitoring, the operation of at least one of the dispersive device and the laser source to  
25 maintain substantial uniformity with respect to time of the output components of the optical pulses.

19. Apparatus as claimed in claim 18 wherein the monitoring means is operable to monitor the output of the waveguide array for a selected one of the spectral lines and to control said operation so as to maximise said output.

20. Apparatus as claimed in any of claims 18 and 19 wherein the control means is operable to control the dispersive device by regulating the temperature of a temperature controlled environment within which the waveguide array is located.

21. Apparatus as claimed in any of claims 18 and 19 wherein said control means is operable to regulate the operating frequencies of the laser source.

22. Apparatus as claimed in any of claims 18 to 21 wherein the frequency selective properties of the waveguide array are matched by the control means to the series of spectral lines from the laser source.

23. A method of optical communication comprising the steps of receiving optical pulses which are multiplexed to define a plurality of channels;  
detecting the pulses to obtain temporally dispersed channel signals for the respective channels; and  
generating clock signals for the respective channel

signals for use in subsequent signal processing;

and wherein the generating step comprises extracting first and second clock signals in respect of first and second channel signals, and determining clock signals for remaining channel signals by interpolation.

24. A method as claimed in claim 23 wherein the first and second channel signals are selected as the earliest and latest received of the channel signals respectively.

10

25. A method as claimed in any of claims 23 and 24 wherein the interpolation is linear with respect to temporal dispersion.

26. A method as claimed in any of claims 23 and 24 wherein the interpolation is non-linear with respect to temporal dispersion.

15

27. A method as claimed in any of claims 23 to 26 wherein each clock signal is derived by adding together weighted versions of the first and second clock signals formed by multiplying said clock signals by respective weights, the weights being varied according to the required interpolation.

20

25

28. A method as claimed in claim 27 including the step of outputting a signal representative of the difference

between the timing of the first and second clock signals; passing the optical pulses prior to detection through a temporal dispersion correcting device; and controlling the temporal dispersion correcting device in response to the output signal to thereby apply dispersion correction to the optical pulses.

29. Receiving apparatus for receiving optical pulses in an optical communication system which are multiplexed to define a plurality of channels, the apparatus comprising; detecting means for detecting the pulses to obtain temporally dispersed channel signals for the respective channels; and

clock generating means for generating clock signals for the respective channel signals for use in subsequent signal processing;

and wherein the clock generating means is operable to extract first and second clock signals in respect of first and second channel signals, and to determine clock signals for remaining channel signals by interpolation.

30. Apparatus as claimed in claim 29 wherein the clock generating means is operable to select the first and second channel signals as the earliest and latest received of the channel signals respectively.

31. Apparatus as claimed in any of claims 29 and 30

wherein the clock generating means is operable to perform interpolation which is linear with respect to temporal dispersion.

5 32. Apparatus as claimed in any of claims 29 and 30 wherein the clock generating means is operable to perform interpolation which is non-linear with respect to temporal dispersion.

10 33. Apparatus as claimed in any of claims 29 to 32 wherein the clock generating means is operable to derive each clock signal by adding together weighted versions of the first and second clock signals formed by multiplying said clock signals by respective weights, the  
15 weights being varied according to the required interpolation.

34. Apparatus as claimed in claim 33 including output means operable to output a signal representative of the  
20 difference between the timing of the first and second clock signals; the apparatus further comprising a temporal dispersion correcting device through which the optical pulses pass prior to detection; and means for controlling the temporal dispersion correcting device in  
25 response to the output signal to thereby apply dispersion correction to the optical pulses.

35. A method of optical communication comprising the steps of;

transmitting a train of optical pulses; and  
multiplexing each pulse to provide a plurality of

5 channels;

the multiplexing step comprising;

modulating the spectrum of the pulse with a set of spectral modulations associated with respective channels such that a respective channel value for each channel is represented by an amount of corresponding spectral modulation, wherein each spectral modulation is defined by a respective characteristic of modulation as a function of frequency and wherein the characteristics are mutually orthogonal in frequency space.

15

36. A method as claimed in claim 35 wherein the characteristics of modulation are sinusoidal modulations in frequency space.

20

37. A method as claimed in claim 36 wherein the spectrum of the pulse is spectrally modulated by means of an array of waveguides, the pulse being divided such that a reference component propagates through a reference waveguide and delayed components propagate through respective delay waveguides before being recombined with the reference component, and wherein the delay waveguides comprise modulating elements selectively controlling the

25

amount of recombination for each delayed component and thereby provide temporal modulation applying channel values for a respective channel.

5 38. A method as claimed in claim 37 wherein the delay waveguides of the array are connected in parallel with one another and with the reference waveguide.

10 39. A method as claimed in any of claims 35 to 38 including the step of modulating the polarisation state of the pulses prior to input to the waveguide array such that successive pulses are transmitted with different polarisation states.

15 40. A method as claimed in claim 37 including the step of modulating the phase of the pulses prior to input to the waveguide array such that successive pulses are transmitted with mutually different phase.

20 41. A method as claimed in claim 37 including the step of controlling the delay waveguides to maintain their respective delay values at respective predetermined values.

25 42. A method as claimed in claim 41 wherein the controlling step is constituted by controlling the temperature of a temperature controlled environment of

the array of waveguides by operation of a temperature controller responsive to an output of the waveguide array.

5 43. A method as claimed in claim 42 wherein the train  
of optical pulses is generated from a pulsed laser source  
having a spectral content comprising a series of spectral  
lines separated by a uniform frequency increment and  
wherein the temperature controller is responsive to the  
10 output of a Mach-Zehnder filter constituted by waveguides  
of the waveguide array arranged such that the output is  
a maximum when a delay waveguide of the Mach-Zehnder  
filter provides a delay which is the inverse of the  
frequency increment.

15 44. A method as claimed in claim 36 including the  
further step of receiving the optical pulses and  
detecting channel values for each respective channel by  
operation of an array of Mach-Zehnder filters each  
20 responsive to a respective characteristic of spectral  
modulation.

45. A method as claimed in claim 44 wherein each of the  
array of Mach-Zehnder filters divides each pulse into a  
25 reference component and a delayed component which is  
delayed relative to the reference component and inputs  
the components to a coupling device which is responsive

to the relative phase of the components, including the step of analysing a differential output of the coupling device to determine a level of spectral modulation representative of a channel value.

5

46. An optical communications system comprising;

a transmitter operable to transmit a train of optical pulses; and

10 multiplexing means operable to multiplex each pulse to provide a plurality of channels;

the multiplexing means comprising;

modulating means operable to modulate the spectrum of the pulse with a set of spectral modulations associated with respective channels such that a  
15 respective channel value for each channel is represented by an amount of corresponding spectral modulation, wherein each spectral modulation is defined by a respective characteristic of modulation as a function of frequency and wherein the characteristics are mutually  
20 orthogonal in frequency space.

47. A system as claimed in claim 46 wherein the characteristics of modulation are sinusoidal modulations in frequency space.

25

48. A system as claimed in claim 47 wherein the modulating means comprises an array of waveguides,

further comprising means for dividing the pulse such that a reference component propagates through a reference waveguide and delayed components propagate through respective delay waveguides before being recombined with the reference component, and wherein the delay waveguides comprise modulating elements operable to selectively control the amount of recombination for each delayed component and thereby provide temporal modulation applying channel values for a respective channel.

10

49. A system as claimed in claim 48 wherein the delay waveguides of the array are connected in parallel with one another and with the reference waveguide.

15 50. A system as claimed in any of claims 46 to 49 including means for modulating the polarisation state of the pulses prior to input to the waveguide array such that successive pulses are transmitted with different polarisation states.

20

51. A system as claimed in claim 48 including means for modulating the phase of the pulses prior to input to the waveguide array such that successive pulses are transmitted with mutually different phase.

25

52. A system as claimed in claim 48 comprising control means operable to control the delay waveguides to

maintain their respective delay values at respective predetermined values.

53. A system as claimed in claim 52 wherein the control  
5 means is a temperature controller operable to control the temperature of a temperature controlled environment of the array of waveguides and wherein the temperature controller is responsive to an output of the waveguide array.

10

54. A system as claimed in claim 53 wherein the transmitter comprises a pulsed laser source operable to generate the train of optical pulses having a spectral content comprising a series of spectral lines separated  
15 by a uniform frequency increment and wherein the temperature controller is responsive to the output of a Mach-Zehnder filter constituted by waveguides of the waveguide array arranged such that the output is a maximum when a delay waveguide of the Mach-Zehnder filter  
20 provides a delay which is the inverse of the frequency increment.

55. A system as claimed in claim 47 comprising a receiver operable to receive the optical pulses and to  
25 detect channel values for each respective channel by operation of an array of Mach-Zehnder filters each responsive to a respective characteristic of spectral

modulation.

56. A system as claimed in claim 55 wherein each of the array of Mach-Zehnder filters is operable to divide each pulse into a reference component and a delayed component which is delayed relative to the reference component, each filter being connected to a respective coupling device such that the components are input to the respective coupling device, wherein each coupling device is responsive to the relative phase of the components, and further comprising means for analysing a differential output of each coupling device to determine a respective level of spectral modulation representative of a respective channel value.

57. A method of optical communication comprising the steps of receiving optical pulses which are multiplexed to define for each pulse a plurality of channels such that a measurable parameter defining a property of the pulse has a first set of distinct values corresponding to respective channels;

detecting each received pulse by means of a detector array comprising detectors which are responsive to a second set of respective values of the parameter and which detectors output respective detector signals;

wherein the second set is greater in number than the first set so that the number of detector signals is

greater than the number of channels;

and analysing the detector signals to extract channel signals representative of channel values carried by the respective channels.

5

58. A method as claimed in claim 57 wherein the detector array defines parameter values of the second set which are outside of a range of parameter values defined by the first set to thereby accommodate systematic drift in the first set of parameter values.

10

59. A method as claimed in any of claims 57 and 58 wherein the number of detectors responsive to parameter values within a range of parameter values defined by the first set is greater than the number of parameter values of the first set.

15

60. A method as claimed in claim 59 wherein at least two detectors are provided for being responsive to each one of the first set of parameter values.

20

61. A method as claimed in any of claims 57 to 60 wherein the optical pulses are multiplexed by wavelength division multiplexing such that the measurable parameter is optical frequency, wherein the detector array is responsive to a range of frequencies greater than the frequency range of the multiplexed pulses in order to

25

accommodate systematic error in the transmission frequencies and systematic error in the frequency response of the detector array.

5 62 A method as claimed in claim 61 wherein frequency components of the received pulse are spatially dispersed and wherein the detectors are spatially arrayed such that at least two detectors are provided for being responsive to each one of the dispersed frequency components.

10

63 A method as claimed in any of claims 57 to 60 wherein the measurable parameter is a characteristic of spectral modulation imposed on a broad waveband optical pulse and wherein each detector comprises a respective  
15 Mach-Zehnder filter responsive to a respective characteristic of spectral modulation.

64 A method as claimed in claim 63 wherein the detector array comprises at least twice as many Mach-Zehnder  
20 filters as the number of spectral modulation characteristics available in the multiplexed pulse.

65. Receiving apparatus for receiving optical pulses which are multiplexed to define for each pulse a  
25 plurality of channels such that a measurable parameter defining a property of the pulse has a first set of distinct values corresponding to respective channels; the

apparatus comprising;

a detector array for detecting each received pulse,  
said array comprising detectors which are responsive  
to a second set of respective values of the parameter and  
5 which detectors output respective detector signals;

wherein the second set is greater in number than the  
first set so that the number of detector signals is  
greater than the number of channels;

and means for analysing the detector signals to  
10 extract channel signals representative of channel values  
carried by the respective channels.

66. Apparatus as claimed in claim 65 wherein the  
detector array defines parameter values of the second set  
15 which are outside of a range of parameter values defined  
by the first set to thereby accommodate systematic drift  
in the first set of parameter values.

67. Apparatus as claimed in any of claims 65 and 66  
20 wherein the number of detectors responsive to parameter  
values within a range of parameter values defined by the  
first set is greater than the number of parameter values  
of the first set.

25 68. Apparatus as claimed in claim 67 wherein the  
detector array comprises at least two detectors for being  
responsive to each one of the first set of parameter

values.

69. Apparatus as claimed in any of claims 65 to 68 operable to receive optical pulses multiplexed by wavelength division multiplexing such that the measurable parameter is optical frequency, wherein the detector array is responsive to a range of frequencies greater than the frequency range of the multiplexed pulses in order to accommodate systematic error in the transmission frequencies and systematic error in the frequency response of the detector array.

70. Apparatus as claimed in claim 69 comprising dispersion means operable to spatially disperse frequency components of the received pulse and wherein the detectors are spatially arrayed such that at least two detectors are provided for being responsive to each one of the dispersed frequency components.

71. Apparatus as claimed in any of claims 65 to 68 wherein the measurable parameter is a characteristic of spectral modulation imposed on a broad waveband optical pulse and wherein each detector comprises a respective Mach-Zehnder filter responsive to a respective characteristic of spectral modulation.

72. Apparatus as claimed in claim 71 wherein the

detector array comprises at least twice as many Mach-Zehnder filters as the number of spectral modulation characteristics available in the multiplexed pulse.

5 73 A method of optical communication comprising the steps of;

transmitting a train of optical pulses;

multiplexing each pulse to carry a set of channels;

receiving the optical pulses;

10 monitoring for each channel a respective error rate in the received pulses;

selecting on the basis of most favourable error rate performance a subset of the set of channels to carry a first data stream;

15 designating remaining channels on the basis of being relatively error prone as non-selected channels to carry a second data stream; and

wherein the first and second data streams comprise respective error detecting codes whereby the monitoring  
20 step determines the error rate performance therefrom.

74. A method as claimed in claim 73 wherein the first data stream comprises user data and parity bits for providing error detection and correction of the user  
25 data.

75. A method as claimed in claim 74 wherein the second

data stream comprises user data at a lower bit rate than the bit rate of user data in the first data stream.

76. A method as claimed in any of claims 73 and 74  
5 wherein the second data stream comprises an error detection code.

77. A method as claimed in claim 74 wherein the first  
10 data stream comprises code words for each respective pulse in which the parity bits are formed by interchannel coding and further defining a frame structure for successive pulses in which user data is serially error coded to provide parity bits in respect of data contained in respective channels.

15 78. A method as claimed in any of claims 73 to 77 including the step of monitoring the error rate performance of the selected subset of channels and the designated non-selected channels, identifying one or more  
20 channels of the selected subset of channels as having a degraded error rate performance, designating the identified channel or channels as non-selected channels and selecting a corresponding number of the previously designated non-selected channels for inclusion in the  
25 subset of channels carrying the first data stream.

79. A method as claimed in claim 78 wherein a designated

non-selected channel replaces an error prone channel of the subset only if its error rate performance exceeds that of the channel of the subset by a factor of at least ten.

5

80. An optical communications system comprising;  
means for transmitting a train of optical pulses;  
multiplexing means operable to multiplex each pulse to carry a set of channels;

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receiving means operable to receive the optical pulses;

monitoring means operable for each channel to monitor a respective error rate in the received pulses;

means for selecting on the basis of most favourable error rate performance a subset of the set of channels to carry a first data stream;

15

means for designating remaining channels on the basis of being relatively error prone as non-selected channels to carry a second data stream; and

20

encoding means for encoding the first and second data streams to comprises respective error detecting codes whereby the monitoring step is operable to determine the error rate performance therefrom.

25

81. A system as claimed in claim 80 wherein the encoding means is operable to encode the first data stream so as to comprise user data and parity bits for providing error

detection and correction of the user data.

82. A system as claimed in claim 81 wherein the encoding means is operable to encode the second data stream so as to comprise user data at a lower bit rate than the bit rate of user data in the first data stream.

83. A system as claimed in any of claims 80 to 82 wherein the encoding means is operable to encode the second data stream so as to comprise an error detection code.

84. A system as claimed in claim 81 wherein the encoding means is operable to encode the first data stream so as to comprises code words for each respective pulse in which the parity bits are formed by interchannel coding and to further define a frame structure for successive pulses in which user data is serially error coded to provide parity bits in respect of data contained in respective channels.

85. A system as claimed in any of claims 80 to 84 wherein the monitoring means is operable to monitor the error rate performance of the selected subset of channels and the designated non-selected channels, and further comprising means for identifying one or more channels of the selected subset of channels as having a degraded

error rate performance, means for designating the identified channel or channels as non-selected channels and means for selecting a corresponding number of the previously designated non-selected channels for inclusion  
5 in the subset of channels carrying the first data stream.

86. A system as claimed in claim 85 wherein the designating means is operable to replace a channel of the subset with a designated non-selected channel only if the  
10 error rate performance of the non-selected channel exceeds that of the channel of the subset by a factor of at least ten.

87. A method of multiplexing optical signals in an  
15 optical communications systems wherein each pulse is generated by a single laser source pulsed at a rate of at least 1 GHz and wherein each pulse is multiplexed to provide at least 1,000 channels.

20 88. A method as claimed in claim 87 wherein the multiplexing step uses one of

- (a) spectral modulation; and
- (b) wavelength division multiplexing

25 89. A method as claimed in claim 87 wherein data carried by the multiplexed pulses in error correction coded using both interchannel and serial error coding.

90. A method of optical communication substantially as hereinbefore described with reference to and as shown in any of the accompanying drawings.

- 5 91. An optical communications system substantially as hereinbefore described with reference to and as shown in any of the accompanying drawings.



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Claims searched: 1-12

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**Patents Act 1977**  
**Search Report under Section 17**

**Databases searched:**

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H4B (BKX, BK8), H4P (PEL, PEP)

Int Cl (Ed.6): H04B: 10/08, H04J: 14/00, 14/02, 14/04, 14/06, 14/08

Other: Online: WPI

**Documents considered to be relevant:**

Category	Identity of document and relevant passage	Relevant to claims
Y	GB 2 275 393 A (Northern Telecom) See especially page 3, line 30, to page 5, line 11.	1 & 7 at least
Y	EP 0 771 091 A2 (AT&T) See especially the abstract and figure 2.	1 & 7 at least
Y	EP 0 654 917 A2 (AT&T) See especially the abstract and figure 2.	1 & 7 at least
Y	US 3 873 825 (Bell Telephone) See especially the abstract and figure 1.	1 & 7 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

